Numerical research of an effective measure for stabilizing floating wind turbines in shallow water

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Abstract

Floating wind turbines are attracting increasing interest in recent years attributed to their lots of advantages in transportation, installation and decommission. However, to maintain their motion stability on the premise of not sacrificing output power is challenging, especially in shallow water. In order to explore a viable solution for this issue, a potential motion stabilization measure is proposed and verified in this paper through conducting a series of numerical researches with the aid of SESAM. In the research, the numerical model of a spar-supported 5 MW floating turbine was developed first to investigate its motion stability in different depths water and under different wave conditions. Then, a new concept of motion stabilizer is proposed with the inspiration of the great contribution of heave plate to suppressing the heave motion of spar structures. But different from the application of a single heave plate, the proposed stabilizer consists of multiple number of heave plates, which are connected to the body of the spar structure via arms. The influences of both the number of heave plates and their arm length on motion stabilization results are then investigated in the numerical research, allowing to explore an optimal design of the proposed stabilizer. Considering the dynamic motions of a floating turbine is mainly affected by sea waves, the motion stabilizing capability of the proposed stabilizer is investigated over a wide range of wave period 4-36 s. It has been found that after applying the proposed motion stabilizer, both the pitch and heave motions of the floating turbine are successfully suppressed within the most range of wave period, especially when the wave period exceeds 12 s. As the average wave period in the North Sea is 15-20 s, it is reasonable to believe that the proposed motion stabilizer is a promising tool to adapt the existing spar-supported floating turbine to the application in nearshore shallow water.

1 Introduction

The R&D of floating wind turbine technology is booming in recent years. The key driver of this is the increased desire to develop floating offshore wind farms. For example, a 30 MW floating wind farm is recently commissioned in Scotland; Marubeni is developing a 16 MW pilot floating wind farm off the coast of Fukushima in Japan; France announced a call for constructing 2 floating wind projects in the following years; and so on. The reasons for explaining this diversion of interest from fixed wind turbine to floating turbine are numerous. But the major reasons are: (1) as opposed to fixed turbine, floating turbine does show lots of advantages in transportation, installation and commission. In particular, the reduced use of those heavy transport and installation vessels will lead to a significant reduction of the cost of a wind project; (2) the extensive use of fixed steel foundations accounts for almost 40% of the total cost of a wind project [1]. Such a high cost purely on steel foundation is unacceptable to the wind farm developers, especially when they are under high pressure of reducing the Cost of Energy (COE) of wind power; (3) wind farms are moving farther from coast. The situation will become worse when the fixed turbines are deployed further offshore, where the water is often deeper than in nearshore water areas. SIEMENS's practice has shown that the application of fixed foundations in deep water will become prohibitively expensive due to the increased use of steel material and especially the increased installation difficulties [2]. For these reasons, floating turbine becomes a plausible choice in the future offshore wind industry. This accounts for the increasing R&D of floating turbines in recent years.

According to the different designs of bottom support structures, the existing concepts of floating turbines can be roughly classified into the following three categories:

(1) Category 1 – supported by spar structures, such as Hywind and Sway turbines;
(2) Category 2 – supported by semi-submersible floaters, such as WindFLoat and Ideol turbines;
(3) Category 3 – supported by tension leg platforms, such as Blue H and PelaStar turbines.

Despite the different designs, the majority of these existing concepts of floating turbines were initially designed for the application in deep water. For example, the Hywind project that was recently commissioned in Scotland was built at a water depth of 95-120 m; the WindFloat turbine was sited at a sea area where water depth exceeds 40 m; PelaStar turbine will be deployed in water depth greater than 60 m; and so on. However, in order to reduce the risks of operating wind farm in deep sea, almost all existing offshore wind farms and those to be developed in the following years are still situated in shallow water. Moreover, such a situation will continue in the near future until a mature and more confident deep sea applicable wind turbine technique is achieved. For example, the 4.8 GW Dogger Bank, one of the largest Round 3 offshore wind projects that are going to be developed in the UK, will be built in only 35m depth water [3]. Then, a question arises, i.e. whether these existing concepts of floating turbines are also applicable to shallow water? If not, how to adapt them to the application in shallow water? To answer this question, the numerical research is dedicatedly organized in this paper. Herein, it is worth noting that due to the limited context of the paper, it is unlikely to investigate the applicability and motion stability of all the existing concepts of floating turbines in a single research. For this reason, only the first category of floating turbines that are supported by spar will be investigated in the following. The reason for selecting this concept of floating turbine for research is on the one hand this concept of turbines are already commercialized, and on the other hand this concept of floating turbines have simple structure and easy to simulate in commercial software.

2 Setup of numerical model

The numerical model of a spar-supported 5 MW floating wind turbine is developed in this section with the aid of SESAM. SESAM is a world renowned offshore structural engineering software developed by DNV for the design and analysis of offshore structures. In this paper, the numerical model of the floating turbine was developed by referring to the NREL three-bladed 5 MW baseline wind turbine [4]. The details of the NREL three-bladed 5 MW turbine are listed in Table 1.

Rated power	5 MW
Rotor orientation	Upwind
Rotor configuration	3 blades
Control	Variable speed, collective pitch control
Drivetrain	Multiple-stage gearbox driven
Rotor diameter	126 m
Hub diameter	3 m
Hub height	90 m
Cut-in wind speed	3 m/s
Rated wind speed	11.4 m/s
Cut-out wind speed	25 m/s
Cut-in rotor speed	6.9 rev/min
Rated rotor speed	12.1 rev/min
Rated tip speed	80 m/s
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg

Table 1: Parameters of the NREL three-bladed 5 MW baseline wind turbine [4].

Assume the turbine is support by a spar foundation, of which the parameters are listed in Table 2.

Spar material	Steel
Spar diameter	7 m
Draft	45 m
Ballast weight	1,200,000 kg
Gravity centre of the turbine	-3 m

Table 2: Parameters of spar foundation.

Based on the turbine and spar foundation parameters listed in Tables 1 and 2, the numerical model of the floating turbine was readily developed. It is shown in Figure 1.

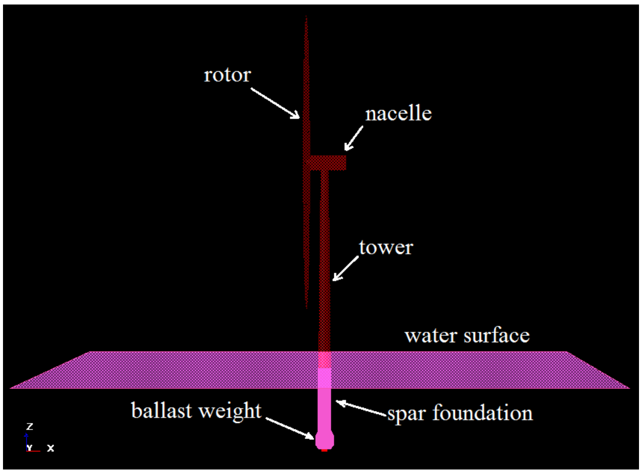


Figure 1: Numerical model of the floating wind turbine

Herein, it is worth noting that mooring system is not yet considered in this research in order to facilitate the investigation of the pure contribution of the proposed motion stabilizer to maintaining a stable floating turbine under various sea wave loading conditions.

3 Stability of a spar-supported floating turbine

The motion stability of a spar-supported floating wind turbine will be investigated in this section. In reality, the dynamic motions of a floating wind turbine can be affected by a number of factors, such as wind above water surface, sea waves on water surface, tidal currents under water surface, mooring system that connect the turbine to the seabed, the strategy of wind turbine control, water depth, and so on. However, among all these influence factors sea waves and water depth are two most important factors that cannot be neglected in the design of a floating wind turbine. For this reason, their influences on the motion stability of a floating turbine will be investigated first in the following.
Assume the turbine is deployed in a certain water area of the North Sea. Considering the significant wave height in the North Sea is higher than 2 m for 60% of time, the mean wave period is 15 – 20 s and it is seldom below 4 s [5], the following scenarios are assumed in the numerical research:

- Scenario 1 – for investigating the influence of water depth on motion stability: wind speed is the rated wind speed of the turbine 11.4 m/s, wave direction is 0°, wave height is 10 m, wave period increases gradually from 4 s to 38 s that cover both calm sea wave conditions and those in storm weathers, and water depth varies in a range of 50 – 1000 m covering both shallow and deep depths waters;

- Scenario 2 – for investigating the influence of waves on the motion stability of the turbine in different circumferential directions: wind speed is still the rated wind speed of the turbine 11.4 m/s, wave height is 10 m, wave period increases gradually from 4 s to 38 s, water depth is fixed at 50 m, and the direction of interest varies from 0° to 90°.

As shown in Figure 2, the power output of a floating turbine is significantly affected by its motions in pitch and heave directions. Particularly, even the weak motion of the turbine in pitch direction may much lower the efficiency of blade pitch control, thus significantly lower the output of the electric power generated by the turbine. For this reason, the pitch and heave motions of the turbine in the first scenario are calculated. The corresponding results are shown in Figure 3.

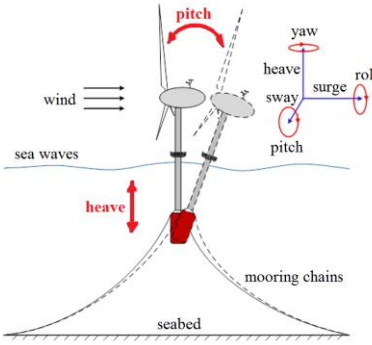
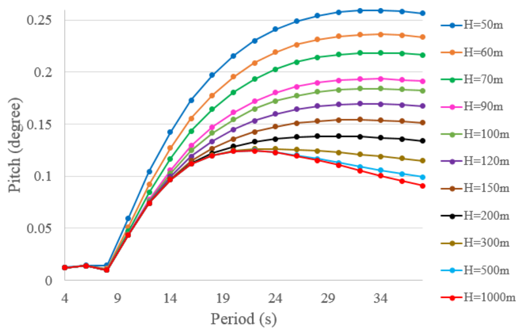
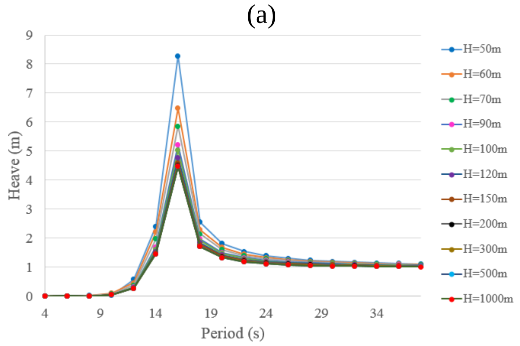


Figure 2: Dynamic motions of a floating wind turbine.



(a)

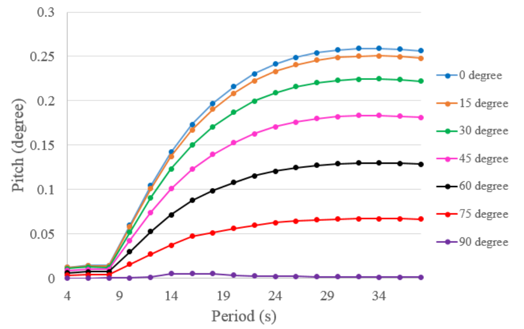


(b)

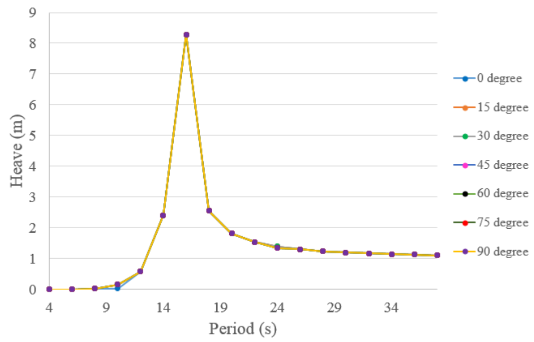
Figure 3: Influence of water depth on the motion stability of the floating turbine, (a) pitch motion, (b) heave motion.

From Figure 3, it is found that in the most range of wave period, both pitch and heave motions of the turbine increase with the decrease of water depth. This implies that it is more difficult to maintain the stability of a floating turbine in shallow water than in deep water. In other words, to apply floating turbine in a shallow water area will have to face more challenges in achieving the desired target of power generation. In addition, with the increase of wave period, the pitch motion of the turbine exhibits a generally increasing tendency. This indicates that the waves with larger wave periods (i.e. longer wave lengths) carry more kinematic energy and thus have more influence on the motion of the floating turbine. In Figure 3b, the wave period 16 s at which the peak heave motion occurs corresponds to the natural frequency of the floating turbine in heave direction.

Subsequently, influences of sea waves on the stability of the floating turbine in different circumferential directions are investigated. The calculation results obtained under the offshore conditions described in Scenario 2 are shown in Figure 4.



(a)



(b)

Figure 4: Wave influence on the stability of the floating turbine in difference circumferential directions, (a) pitch motion, (b) heave motion.

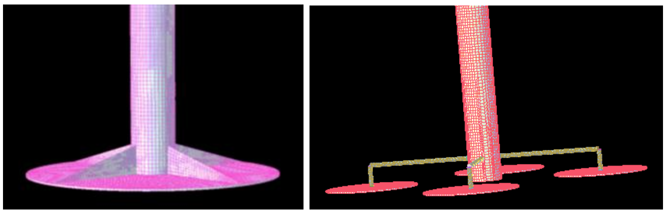
From Figure 4a, it is found that the sea waves have the largest influence on the pitch motion of the turbine in inline direction (i.e. the direction of 0°), which is same as the wave direction. While, the sea waves have less influence on the pitch motion of the turbine in other crossflow directions. In other words, the wave influence on the pitch motion will decrease gradually when the direction of interest deviates from the inline direction until the minimum influence when the direction of interest is perpendicular to the wave direction (i.e. the direction of 90°). From Figure 4b, it is clearly seen that the influence of sea waves on the heave motion of the turbine is unrelated to the direction of interest.

In summary, the calculation results shown in Figures 3 and 4 matches very well with the expectation. This suggests that the numerical model established in Section 2 is completely right. Therefore, the numerical research results that are obtained based on this model are reliable.

4 Design of a new concept of motion stabilizer

The calculation results shown in Section 3 have disclosed that it is difficult to maintain the motion stability of a floating turbine in shallow water. Then, how to overcome this issue and adapt the existing spar-supported floating turbine to the application in shallow water? In fact, some measures have been developed before to stabilize floating wind turbines, although they failed to consider the influence of water depth on the stability. Among these measures, the most popular one is to maintain the stability of the turbine via blade pitch control [6, 7]. However, the blade pitch control method only mitigates the influences by wind, it is unable to suppress the unstable motions caused by sea waves. In addition, the blade pitch control is implemented based on the 10 minutes wind farm SCADA data. Thus, it fails to quickly respond to the instantaneous changes of wind and wave loads. Finally, it becomes very difficult or even impossible to achieve an accurate blade pitch control when the pitch motion of the floating turbine is large. Thus, how to enable the turbine to respond quickly and correctly to the instantaneous changes of both wind and wave loads and moreover stabilize the turbine without sacrificing the output of electric power is still an open question remaining to be resolved today. The research conducted in this section is to address this issue.

Inspired by the positive contribution of heave plate to suppressing the heave motion of spar structures [8, 9], a passive concept of motion stabilizer is proposed in this paper. But instead of using only a single heave plate, it is proposed to use multiple number of heave plates to construct the motion stabilizer. To ease understanding, the diagrams of the conventional method of using a single heave plate and the proposed concept of motion stabilizer that uses multiple number of heave plates are shown in Figure 5.



(a) (b)

Figure 5: Diagrams of the motion stabilizer, (a) conventional method of using a single heave plate, (b) proposed concept of stabilizer using multiple number of heave plates.

It is necessary to note that the proposed concept of motion stabilizer that uses multiple number of heave plates is not a simple copy of the conventional method of using a single heave plate. This is because, in comparison of the conventional method, the proposed motion stabilizer shows many merits in site application and a lot of advantages in motion stabilization. These merits and advantages are briefly summarized below:

(1) In contrast to the large single plate, the multiple number of heave plates that are adopted in the proposed concept of stabilizer are much smaller in size. Thus, they are easier to manufacture and particularly easier to install and replace at site. From this point of view, the proposed motion stabilizer is more ideal for site application;

(2) In the conventional method, part of the surface of the single heave plate is occupied by the bottom surface of the spar. Therefore, the wet surface of the heave plate is reduced. Consequently, the reduced wet surface will significantly decrease the heave motion damping generated by the plate. By contrast, the surface of all heave plates used in the proposed stabilizer is exposed in water. Therefore, from this point of view the proposed concept of stabilizer has fully utilized the contribution of the heave plates to heave motion damping, while the conventional method has not;

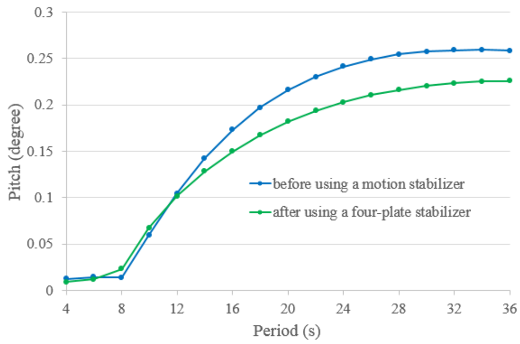
(3) In addition, in the proposed design of the motion stabilizer, the heave plates are connected to the body of the spar via arms. In accordance with the conservation law of momentum, these arms will further enhance the motion stabilization capability of the stabilizer. However, the conventional method of using a single heave plate does not have such a specific feature.

Based on the above discussion, the proposed concept of motion stabilizer should be more effective in stabilizing a floating wind turbine than the existing method does.

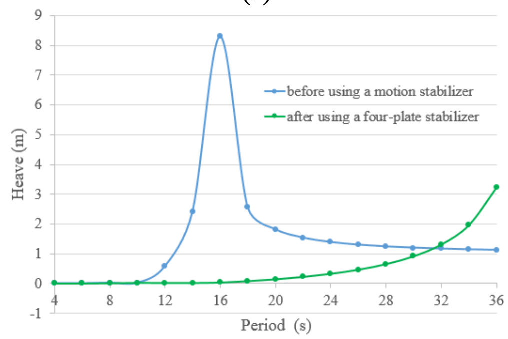
5 Numerical verification of the proposed concept of motion stabilizer

In this section, a four-plate stabilizer is applied to the floating turbine in order to demonstrate the effectiveness of the proposed concept of motion stabilizer in suppressing the motion of the floating turbine. The four heave plates used in the stabilizer are identical to each other. Their diameter is 10 m, thickness is 0.1 m, and the total surface area of the four plates is 1257 m^2. The mass of these four plates are treated as part of the ballast weight of the floating turbine. Herein, it is necessary to note that the heave plates used in the proposed stabilizer are in fact hollow inside. This is why they have 0.1 m thickness. The purpose of such a specific design is to reduce the total weight of the stabilizer while acquiring sufficient damping force. To facilitate the verification, the pitch and heave motions of the spar-supported turbine before and after using the stabilizer are calculated. The corresponding results are shown in Figure 6.

From Figure 6a, it is seen that after using the four-plate stabilizer, the pitch motion of the floating turbine has been suppressed in the most range of wave periods with the exception of 7-12 s. This is not surprised because the wave period range 7-12 s is the range of resonant frequency of the floating turbine in pitch direction after it is equipped with the four-plate stabilizer. In spite of this, the pitch motion of the turbine is significantly reduced by the four-plate stabilizer when the wave period is larger than 12 s. Since the average wave period in the North Sea is 15-20 s, the calculation results shown in Figure 6a indicate that the four-plate stabilizer is not only able to successfully stabilize the floating turbine in normal operation, but also able to protect the turbine and reduce its risk of sinking in the storm weather conditions. From Figure 6b, it is seen that after using the four-plate stabilizer, the resonant frequency of the turbine in heave direction has been significantly reduced due to the large damping introduced by the heave plates. In other words, the resonant heave motion occurs at wave period 16 s before using the stabilizer, while the resonant heave motion is never observed over the whole range of wave period 4-36 s after the turbine is equipped with the four-plate stabilizer. As mentioned earlier, the average wave period in the North Sea is 15-20 s, this suggests that the proposed concept of motion stabilizer is really helpful in achieving the desired stability of a North Sea floating wind turbine in both pitch and heave directions.



(a)



(b)

Figure 6: Verification of the proposed concept of motion stabilizer, (a) pitch motion, (b) heave motion.

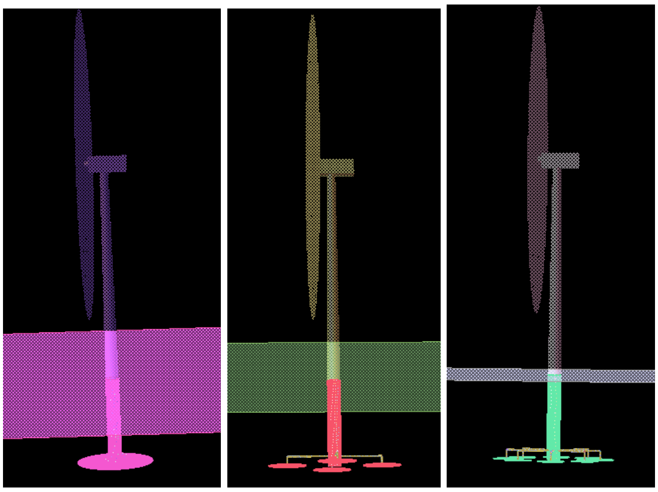
6 Advantages of the proposed motion stabilizer over the conventional method

Furthermore, the advantages of the proposed concept of motion stabilizer over the conventional method of using a single heave plate is demonstrated in this section through calculating and comparing the pitch motions of the turbine that is equipped with different concepts of motion stabilizers. In the calculation, total three concepts of stabilizers are considered. They are single-plate stabilizer, four-plate stabilizer, and eight-plate stabilizer, respectively. In order to ensure all calculation results obtained after using different stabilizers are comparable, the total surface area of the heave plates is assumed same whatever how many number of heave plates are used to build the motion stabilizer. Moreover, to further assure the comparability of the calculation results, the mass of the heave plates will be treated as part of the ballast weight of the floating turbine. The ballast weight of the floating turbine will be kept same in all numerical research scenarios. The geometries that are used in different stabilizer designs are listed in Table 3.

Stabilizer concept	Number of plates	Diameter of plate	Arm length	Total surface area
I	1	40 m		1257 m^2
II	4	20 m	20 m	1257 m^2
III	8	14 m	20 m	1257 m^2

Table 3: Geometries used in the different stabilizer designs.

Based on the above designs, the three concepts of motion stabilizers are simulated. The floating turbines that are respectively equipped with the three concepts of motion stabilizers are shown in Figure 7.



(a) (b) (c)

Figure 7: Floating wind tubrines that are equipped with different concepts of motion stabilizers, (a) Concept I stabilizer, (b) Concept II stabilizer, (c) Concept III stabilizer.

Then, the pitch motions of the turbine after being equipped with different concepts of stabilizers are calculated. The calculation results are shown in Figure 8.

Form Figure 8, it is clearly seen that over the whole wave period range of 4-36 s, the Concept II and Concept III motion stabilizers are indeed superior to the Concept I stabilizer that uses only a single heave plate in stabilizing the pitch motion of the turbine. This means that after equipping with the proposed multi-plate motion stabilizer, the floating turbine can achieve better stability in pitch motion, although the multiple number of heave plates used in the new designs have the exactly same surface area as that of the single heave plate used in the conventional design. Moreover, the further comparison of the results shown in Figure 8 discloses that the more number of heave plates are used to construct the stabilizer, the better motion stabilization can be achieved.

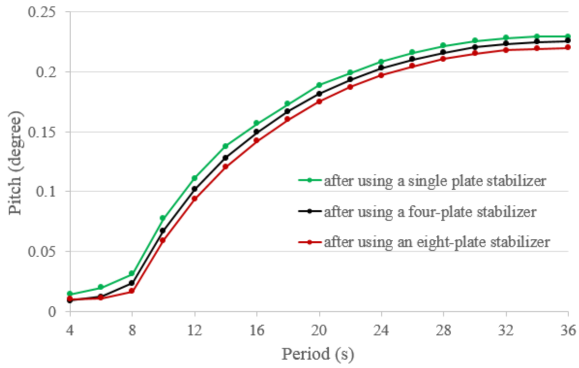


Figure 8: Pitch motion of the floating turbine equipped with different concepts of motion stabilizers.

As mentioned earlier, the heave plates that are used in the proposed concept of motion stabilizer are connected to the body of the spar structure via arms and it is predicted in Section 4 that the utilization of these arms may further enhance the motion stabilization capability of the motion stabilizer. In order to prove this prediction, the influence of the arm length on the motion stabilization is investigated. Herein, the application of the eight-plate stabilizer is considered. When the arm length is respectively set to be 20, 25 and 30 m, the corresponding pitch motion calculation results are shown in Figure 9.

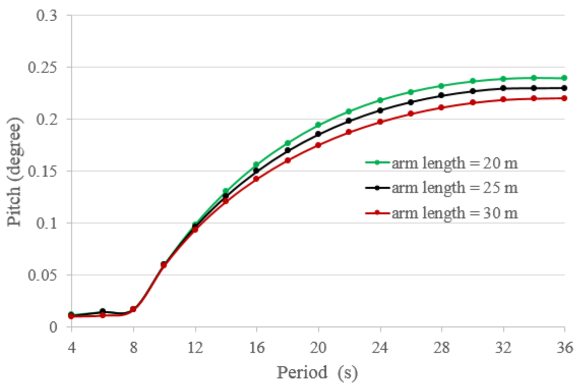


Figure 9: Influence of the arm length on motion stabilization.

From Figure 9, it is observed that with the increase of the arm length, the pitch motion of the floating turbine decreases over the most range of wave period, especially when the wave period is larger than 12 s. Since the average wave period in the North Sea is 15-20 s, such calculation results indicate that the application of the arms in the proposed motion stabilizer does enhance the motion stabilization capability of the stabilizer when the stabilizer is applied to the floating turbines operating in the North Sea.

7 Conclusions

Inspired by the positive contribution of heave plate to suppressing the heave motion of spar structures, a new motion stabilization measure is proposed and numerically verified in this paper in order to adapt the existing spar-supported floating wind turbine to the application in shallow water. From the numerical calculation results described above, the following conclusions can be drawn:

(1) It is more difficult to maintain the stability of a floating turbine in shallow water. Since the power generation efficiency of a floating turbine is highly dependent on its motion stability, the application of floating wind turbines in shallow water will have to face more challenges in operation as the desire target of power generation is not easy to be achieved due to the instable motions of the turbine, especially the instable motion of the turbine in pitch direction;

(2) In contrast to the conventional method that uses only a single heave plate, the proposed concept of motional stabilizer is more suited to site use and moreover has many advantages in motion stabilization. Particularly, the arms that connect the heave plates to the body of spar can further enhance the motion stabilizing capability of the stabilizer;

(3) The calculation results have shown that the proposed motion stabilizer can successfully suppress the pitch and heave motions of the spar-supported floating turbine when the wave period is over 12 s. As the average wave period in the North Sea is 15-20 s, it is reasonable to believe that the proposed motion stabilizer is a promising tool to adapt the existing spar-supported floating turbine to the application in nearshore shallow water.

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